INVESTIGATING THE INTEGRATION OF A SOLID OXIDE FUEL CELL AND A GAS TURBINE SYSTEM WITH COAL GASIFICATION TECHNOLOGIES

A THESIS

Presented to
The Faculty of the Division
of Graduate Studies
By
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In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Mechanical Engineering

Georgia Institute of Technology

September, 2001

INVESTIGATING THE INTEGRATION OF A SOLID OXIDE FUEL CELL

AND A GAS TURBINE SYSTEM

WITH

COAL GASIFICATION TECHNOLOGIES

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ACKNOWLEDGEMENTS

I am extremely thankful for all who assisted or supported me not only during my thesis construction but also during my attendance at Georgia Tech. First of all I would like to thank my Lord and Savior Jesus Christ, who has given me an unction to know all things concerning his wisdom and his peace which passes all understanding. I would also like to thank my wife Michelle and my three children Troy, Gabrielle, and Addison for supporting and loving me while working and studding here at school.

I would also like to thank the members of my reading committee, Dr. Wepfer, Dr. Jeter, Dr. Shelton, and Dr. Comas Haynes for not only taking time out of their busy schedules to be here but also for their guidance and suggestions during the construction of my thesis. I would especially like to thank Dr. Wepfer and Dr. Haynes for allowing me the opportunity to work on this project.

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NOMENCLATURE

Symbol	Definition
η	Efficiency
I	Current
V	Voltage
E	Nerst Potential
R	Recuperator Effectiveness
NOS	Stoichiometric Number
m	Mass Flow Rate
P	Pressure

SUMMARY

Solid oxide fuel cell (SOFC) technology incorporates electrochemical reactions that generate electricity and high quality heat. The coupling of this technology with gas turbine bottoming cycles, to form hybrid power systems, leads to high efficiency levels. The purpose of this study is to conceptually integrate the hybrid power system with existing and imminent coal gasification technologies. The gasification technologies include the Kellogg Brown Root (KBR) Transport Reactor and entrained coal gasification.

Parametric studies will be performed wherein pertinent fuel cell stack process settings such as operation voltage, inverse equivalence ratio and fuel utilization will be varied. Power output, system efficiency and costs will be the dependent variables of interest. Coal gasification data and a proven SOFC model will be used to test the theoretical integration. Feasibility and economic comparisons between the new integrated system and existing conventional systems will also be made.

CHAPTER I

INTRODUCTION

1.1 Motivation

As the search continues for alternative power and resources in the United States as well as in many other industrialized countries around the world, the concept of reducing pollution and increasing efficiency at a cost which will be paid back over a reasonable period of time will always be in high demand. The price for not seeking alternative resources of power or using systems which will consume only a fraction of our present day fuels can be seen in California. For the past several months the State of California has been subjected to rolling blackouts. Among the reasons why the state of California is in this situation include their inability to import enough power due to their own partial deregulation laws, and their current power plants are unable to produce a sufficient amount of power during all the time periods that the consumer wants.

A definite shortage in power generation capacity exists in California and incentives have been instituted to create more power plants; however, the increase in natural resource consumption will definitely increase as well as pollution. So how can this consumption of natural resources be slowed down and the efficiency of the power plants increase, while at the same time the environment is not being harmed by the pollutants that the power plant combustion processes produce? One way is the use of

fuel cell technology. Fuel cell technology is currently one of the best means for direct conversion of chemical energy to electrical energy, and it also has a high temperature exhaust which introduces the possibility of multiple cogeneration applications as well. At present, many of the United States' power supply companies use some form of pulverized coal technology and in turn also produces some pollutants in the exhausted waste. Southern Company is testing a new type of coal gasification technology which converts coal into a gaseous fuel and could raise the standard in coal gasification technology. This new standard could lead to a cleaner and lower cost of electric power generation as well as a more efficient means of producing electricity. Integrated Gasification Combined Cycle (IGCC) systems may soon completely replace conventional pulverized coal (PF) systems if the Department of Energy can reach their projected goal of $1000 per kilowatt and an efficiency (based on HHV) of 52% in the year 2008.[1] With current average IGCC capital cost of $1250 per kilowatt and a HHV efficiency of 42% for the year 2000, conventional pulverized coal systems are still the dominate source for energy generation and are still in use around the world.[1] Also these pulverized coal fired power plants create a large amount of air pollution which are currently causing environmentalist to lobby for new ways of producing energy without pollution. Thus the theoretical concept of integrating fuel cell technology with gasifier technology is being researched.

[1]Department of Energy (online). Available: http//www.fe.doe.gov/programs_Coalpwr.html

1.2 The Fuel Cell

The fuel cell is a clean and efficient device which electrochemically converts chemical fuel into electricity. The fuel cell combines a variety of hydrocarbon fuels such as natural gas, methanol, gasoline, propane, oxygen etc., to produce electricity. All basic fuel cells consist of an anode, a cathode, and an electrolyte, which is similar to a battery. The difference between the battery and a fuel cell is the fact the when the chemical reactant stored in the battery is consumed, then the battery is at the end of its usefulness and is either recharged or discarded. In a fuel cell the fuel source is replaced continuously while it is in motion. The fuel cell processor converts the available hydrocarbon fuel to a hydrogen rich gas which in turn is fed to the fuel cell. The power section contains the fuel cell stack, this stack has a series of electrode plates which are connected to produce a desired amount of Direct Current (DC) power. The DC power is then converted to AC power when needed.

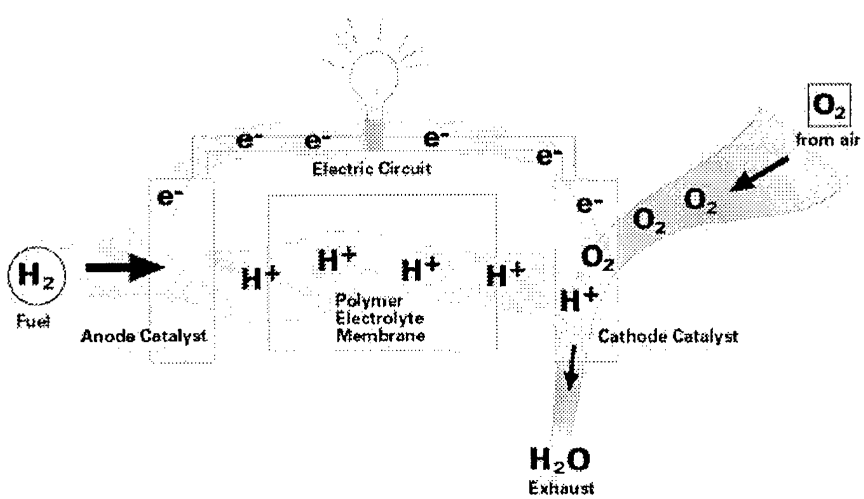

Figure 1.1 Basic Fuel Cell

1.3 The Gasification System

The Integrated Gasification Combined Cycle (IGCC) is considered to be one of the best alternative technologies when compared to the present conventional pulverized coal combustion technology which generates electricity from coal. The pulverized coal technology is still the dominant system in both new and existing coal fired power plants in many areas of the world; however, an increasing number of commercial scale IGCC plants has already begun, making an impact on electricity generation and lower levels of pollution. The IGCC plant combines a coal gasification unit with a gas fired power generation plant cycle. This cycle will enable the IGCC to produce electricity from coal with a higher level of efficiency and with a very low level of emissions. Gasification is achieved by reacting the coal with temperatures and pressures around 1600F and 20 atm and with a very limited amount of oxygen. This IGCC concept produces a fuel gas which mainly consists of carbon monoxide and hydrogen which then passes through a clean up stage that removes the sulfur and nitrogen particulates. After passing through the clean up stage, the cleaned gas is burnt in a conventional gas powered turbine which will produce the electric power. Most current IGCC development is tested and performed on fluidized beds or entrained flow gasifiers. The fluidized bed gasifiers are better suited for low rank or quality coals, while the entrained flow gasifiers prefer the high rank or quality type of coals. The economic advantages of the IGCC, which will be explained in greater detail in Chapter 5, are the use of low cost feedstocks, high efficiencies, and its

reduction of environmental pollutants when compared to existing fossilized fuel and pulverized coal power plants. In addition the IGCC's by products such as sulfur are also marketable. The IGCC uses regenerable sorbents and catalysts so the costs of replenishing and disposing these supplies are minimized. The U.S. Department of Energy is also assisting in the study, testing, and improvement of the IGCC; however, integrating the IGCC with other efficient power generating systems is also being researched.

CHAPTER II

FUEL CELLS AND GASIFIERS

2.1 Overview

The search for alternative power sources which are cheaper, more efficient, and do not harm the environment while at the same time have the ability for minimal consumption of our natural resources is a continuous process. Technology continues to develop a variety of electricity generating systems, but the process of research and integration into existing systems is a time consuming process. Two premiere technologies, fuel cell and Integrated Gasification Combined Cycle (IGCC) systems, have both proven themselves individually to be a cleaner, more efficient, and reliable alternative to existing power generation technologies. As of 1988 eight IGCC plants were constructed and are now operating in the domestic and international petroleum refining industries. Studies have already shown that the capital cost for a natural gas combined cycle is currently about one half the cost of a coal IGCC plant. These IGCC systems can also be used to convert hazardous waste into useful products. The electric power industry as well as the U.S. Department of Energy (DOE) are fully aware that the IGCC will be a leading candidate to provide a higher level of power which will be able to keep up with the projected increases in electric capacity consumption. The possibility of physically integrating these two systems could lead to a new generation of power plants.

2.2 Types of Fuel Cells

Fuel cell technology not only continues to improve upon existing technology, but also has started to create improved technologies because of the various needs of power generation systems with high efficiencies. There are several varieties of fuel cells which can be characterized either by shape, electrolyte composition, or operating temperature. The different electrolyte compositions, molten, solid, and aqueous play a major role in fuel cell operation parameters, conditions, and applications such as vehicular power supply, stationary, or space craft/station power.

2.2.1 Alkaline Fuel Cells

The Alkaline Fuel Cell, is currently being used in space applications because of its relatively high efficiency and voltage output. The Alkaline Fuel Cell is designed to convert pure oxygen and hydrogen into electricity. Due to this fact, the cost for operating a fuel cell of this nature is relatively high; however, the operating temperatures range between 80 to 150 F. The military is also constantly looking for alternative forms of power generators which do not produce high heat signatures which can show up on many enemy weapon system's optics. The Alkaline Fuel Cell is currently a leading candidate for military ground applications when compared with other fuel cells.

2.2.2 Phosphoric Acid Fuel Cell

The Phosphoric Acid Fuel Cell is commercially available today and well over 300

fuel cells of this kind have been installed all over the world in common places of business such as hospitals, hotels, schools, utility power plants, and airport terminals. The Acid Fuel Cell uses phosphoric acid to generate electricity at more than 40% efficiency. The operating temperatures range between 350 to 400 F. Also, approximately 85% of the steam that the Acid Fuel Cell produces can be and in many cases is used for cogeneration. Because of the increase in industrial applications, efforts have been made to continually up-grade the Acid Fuel Cell and reduce the minor corrosion problems to an even lower level.

2.2.3 Proton Exchange Membrane

The Proton Exchange Membrane (PEM) Fuel Cell operates at a temperature range of approximately 190 to 200 F. The PEM fuel cell has very high power density and one of the few fuel cell technologies that can vary its output quickly to meet shifts in power demand. Because of its design, this particular fuel cell is best suit for possible applications in automobiles in which a fast startup is necessary. The Department of Energy has also stated that the Proton Exchange Membrane Fuel Cell is the "primary candidate for light-duty vehicles, for buildings, and potentially for much smaller applications such as replacements for rechargeable batteries." This fuel cell uses a thin plastic sheet that is designed to allow hydrogen ions to pass through it. The hydrogen enters on the anode side of the fuel cell where a catalyst is located and causes the hydrogen atoms to release electrons and become hydrogen ions. It is here that the electric

current is generated and will be utilized before returning to the cathode side of the fuel cell.

2.2.4 Regenerative Fuel Cells

The Regenerative Fuel Cell is one of the newest additions to the fuel cell community. This fuel cell uses a closed-loop form of power generation where water is separated into its basic elements of oxygen and hydrogen. This is accomplished by the solar-powered electrolyser outside the fuel cell. The oxygen and hydrogen are then released into the fuel cell which will in turn generate electricity, heat and water. This water is then recycled back into the solar-powered electrolyser and repeating the cycle. Currently the U.S. Military and NASA along with other engineering firms specializing in fuel cell technology are researching its future applications and usefulness.

2.2.5 Molten Carbonate Fuel Cells

The Molten Carbonate fuel cell has one of the higher fuel-to-electricity efficiencies when compared to other fuel cell systems and, it and operates at about 1,200 F. These fuel cells have are able to operate on hydrogen, carbon monoxide, natural gas, propane, landfill gas, marine diesel, and simulated coal gasification products. Many of the stationary applications for this fuel cell have been successfully tested in Japan.

2.2.6 Solid Oxide Fuel Cells

The Solid Oxide Fuel Cell (SOFC) is the main fuel cell technology this thesis will be focusing on. The SOFC is designed to be used in large, high-power applications such as industrial and large-scale central electricity generating stations. The military is also considering using solid oxide fuel cells as their tank and other armored vehicle's auxiliary power units (APUs). A SOFC system uses a hard ceramic material which is completely different from the previous fuel cell's liquid electrolyte concept. The approximate operating pressures are between 3-5 atmospheres and temperatures up to 1,800 F. SOFC electrical generating efficiencies average between 65 and 70%. Recent demonstrations of tubular SOFC stacks have produced a power output as high as 200 kW. Currently, the average cost for a fuel cell plant is $3000 per kW. Several companies around the world are currently producing SOFC designs (figure. 2.2.1).

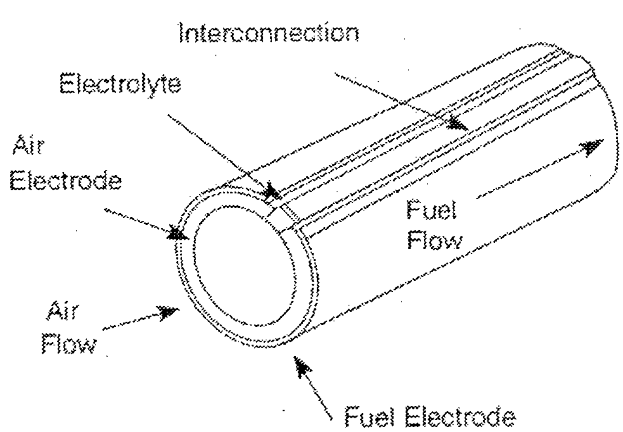

Figure 2.2.1 Solid Oxide Fuel Cell

2.3 Types of Gasifiers

The Integrated Gasification Combined Cycle (IGCC) currently meets all projected environmental regulations while at the same time producing high value products (according to the DOE). Some products generated by the IGCC are hydrogen, premium chemicals, and transportation fuels that have the potential to increase our nation's energy security because of domestic production of these fuels. The different IGCC systems were designed for different types of applications. In the industrial field, coproduction, or cogenerations applications mainly use fixed bed technology, and for coal refinery and waste applications fluidized bed or entrained gasification technology is more suitable.

2.3.1 Lurgi Fixed-Bed Gasifier

The British Gas/Lurgi Fixed Bed gasifier uses steam and oxygen as its oxidant and operates between 20-30 atm. at a reaction temperature of 1,100 C. Its ash handling method is dry. The Lurgi gasifier receives coal and briquettes which enter into the top portion of the gasifier, while steam and oxygen enter at the bottom. As the coal and briquettes reach the grate and are burned, the gaseous fuel passes through a clean up stage where oils and particulates (called slag) are removed. The clean gas exits near the top of the gasifier and is used to power conventional gas turbines.

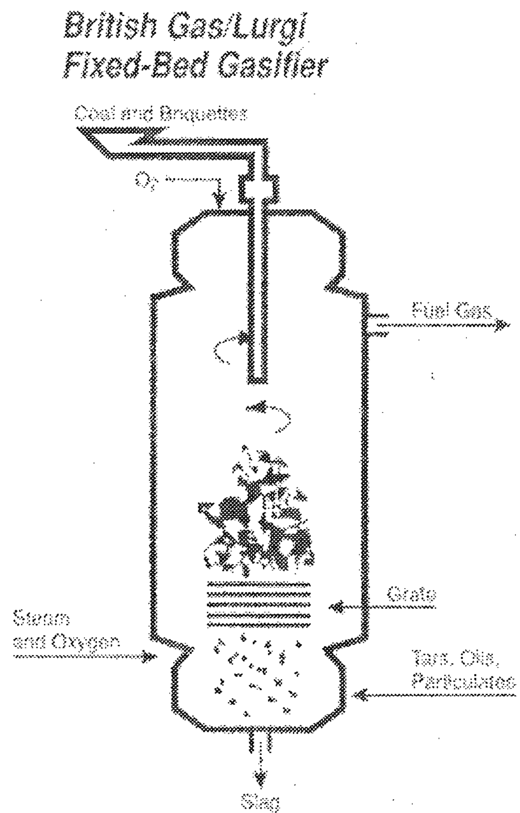

Figure 2.3.1 British Gas/Lurgi Fixed-Bed Gasifier

2.3.2 Texaco Entrained Flow Gasifier

The Texaco Etrained Flow (Downflow) gasifier uses oxygen as its oxidant and operates between 20-30 atm. with a reaction temperature of 1,200-1550 C, and the ash handling method is slagging. The Texaco gasifier uses the down flow fuel method by simultaneously feeding coal slurry and oxygen into the top of the gasifier where it is immediately burned, then the synthesis gas exits near the bottom and is used to power a conventional gas turbine. At the same time water passes through heat exchanger system

inside the gasifier and exits as steam and is used to power steam turbines. The remaining oils and particulates (called slag) are removed at the very bottom of the gasifier.

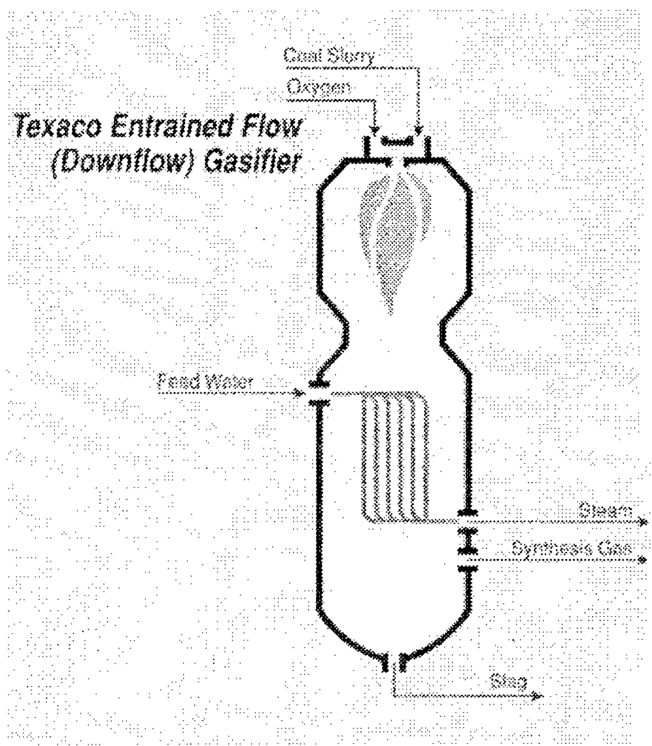

Figure. 2.3.2 Texaco Entrained Flow Gasifier

2.3.3 KRW Fluidized Bed Gasifier

The KRW Fluidized Bed gasifier uses air as its oxidant and operates at 20 atm. with a reaction temperature of 950-1,100 C, and the ash handling method is dry. The KRW gasifier uses the up flow fuel method by simultaneously feeding coal, limestone, air, and a small percentage of recycled gas the bottom of the gasifier where it is

immediately burned, then the synthesis gas exits at the top (after passing through a clean-up stage) and is used to power a conventional gas turbine. The remaining oils and ash are removed at the bottom of the gasifier.

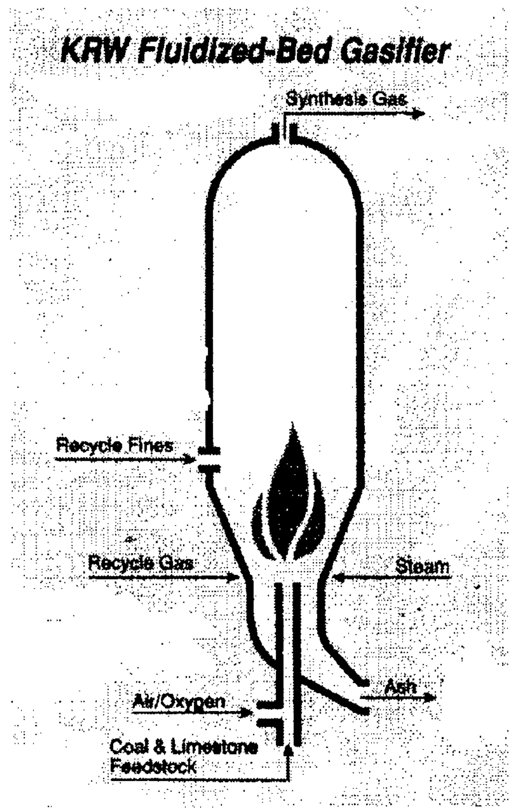

Figure. 2.3.3 KRW Fluidized-Bed Gasifier

2.3.4 Destec Entrained Flow Gasifier

The Destec Entrained Flow (up flow) gasifier uses oxygen as its oxidant and operates at 30 atm. with a reaction temperature of 1,400-1,550 C, and the ash handling method is slagging. The Entrained Flow gasifier uses the "up flow" fuel method by

simultaneously feeding coal slurry in two different places at the bottom and middle and oxygen and char at opposite ends on the bottom. As the fuel is then the synthesis gas exits at the top (after passing through a clean-up stage) it is used to power a conventional gas turbine. The remaining oils and ash are removed at the bottom of the gasifier.

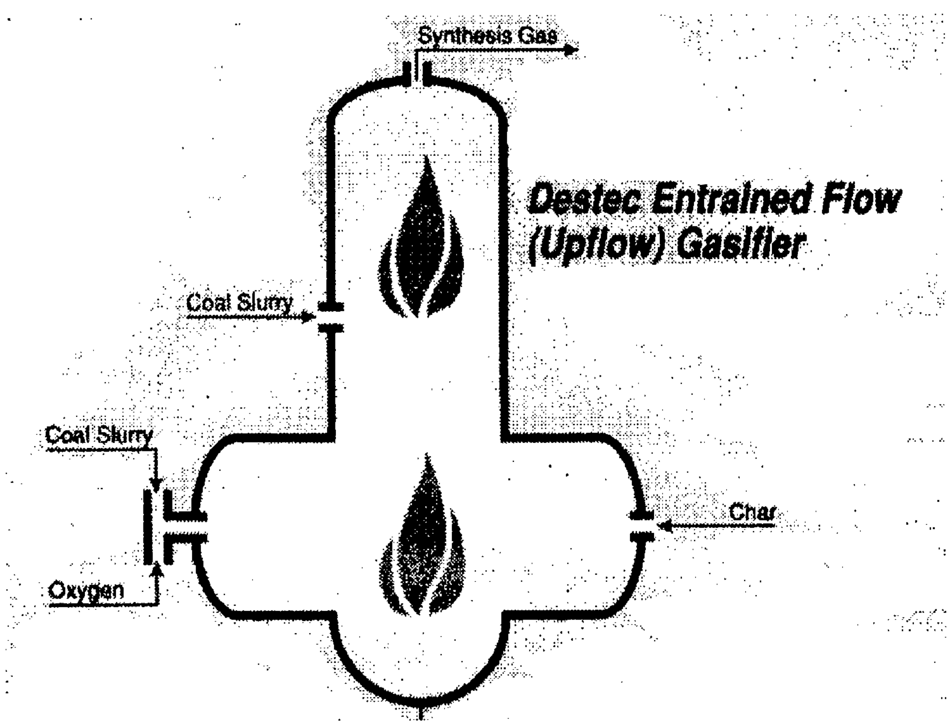

Figure. 2.3.4 Destec Entrained Flow Gasifier

2.3.5 Kellogg Transport Reactor Gasifier

The Kellogg Transport Reactor gasifier, being investigated in this study, is a circulating fluidized bed reactor which can operate as a combustor or gasifier. Coal and air are fed into the reactor at the mixing zone section while the disengager removes a

large amount of solids from the gas. From this point the flow is separated and travels down through a vertical standpipe which is connected to the cyclone. The cyclone removes additional particles from the gas stream. The solid particles then move back to the mixing zone where it is removed from the system during the particulate clean up stage. In combustion mode a slipstream of solids will go through a combustor heat exchanger and back into the bottom of the mixing zone so that the reactor temperature is at a reasonable controllable level.

1. Mixing zone
2. Riser
3. Disengager
4. Standpipe
5. Primary Cyclone
6. Dipleg
7. Combustor Heat Exchanger
8. Reactor j-leg
9. Combustor Heat Exchanger j-leg
10. Start-up Burner Inlet

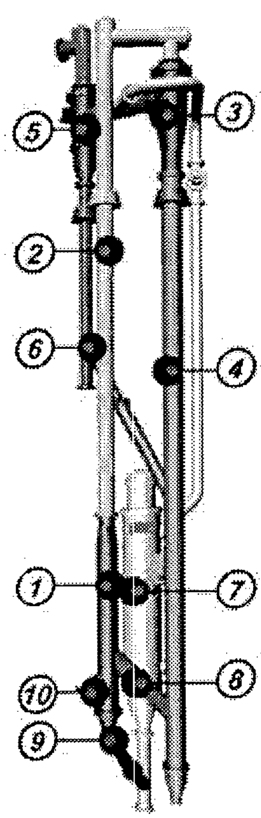

Figure. 2.3.5 Kellogg Gasifier Description and Schematic

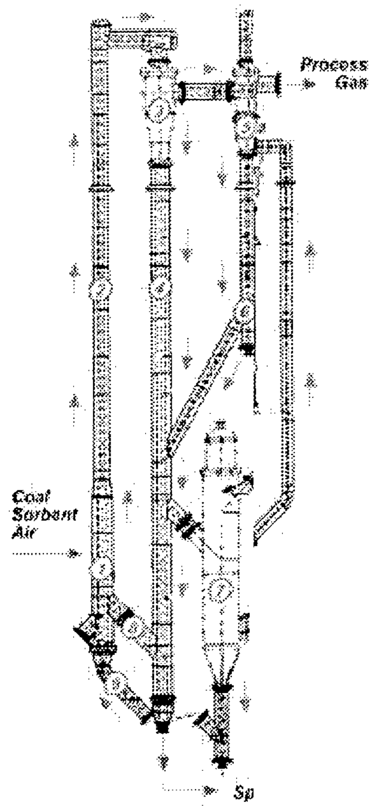

Figure. 2.3.6 Kellogg Gasifier Description of flow

The particulate clean up stage uses two particulate control devices (see figure 2.3.7), at high temperatures and pressures the particulate clean-up device (PCD) filters ash and char and allows clean gas to flow through and exit at the top end of the system. Using a backwards flow of air will then allow the ash and char to be removed from the filters and collect at the bottom of the PCD pressure vessel and subsequently out of the system.

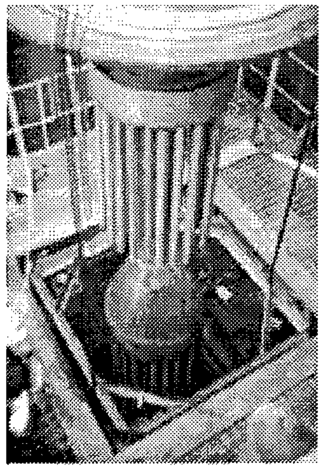

Figure. 2.3.7 Particulate Control Device (Filter)

Some basic economics and specifications of the Kellogg Transport Reactor are:

Type:	500MW air blown IGCC
Average Cost	Below $890/kW for a plant with a heat rate of 7000 Btu/kWh
Reactor Temperature	1,575-1,625 F
Pressure	16-22 atm
Coal feed	900-3500lb/hr ft^2
Heat Release rate	45MBtu/hr ft^2

Table 2.3.1 Cost/description of the Kellogg Transport Reactor

A working Kellogg Transport reactor is currently located in Wilsonville Alabama and is operated by Southern Company Services.

CHAPTER III

PROBLEM DEFINITION

3.1 Description of Study

The integration of a solid oxide fuel cell (SOFC) with a gas turbine system will focus primarily on the electrochemical reaction that generates electricity from a gaseous fuel coupled with the gas turbine bottoming engines so that a hybrid power system is formed. The gas turbine may operate as an open system when it is used as a truck engine or United States Army M1A1 tank engine, or as a closed cycle when it is used in conjunction with some power plants. The ideal cycle which engineers use to model a basic gas turbine is the idealized Brayton cycle. The Brayton cycle utilizes isentropic expansion and compression. This cycle system consists of a gas turbine, a compressor, a heat exchanger and combustor. Modifications were made to the standard Brayton cycle by the addition of another compressor and an intercooler. This modification will lead to higher efficiency levels. In a Brayton cycle some turbine output will be used to drive the compressor while the rest of the turbine work is distributed outside the power plant to assist in power requirements and needs for the consumer. During this process the compressor sends compressed air to a combustor where it is mixed with fuel from the fuel cell stack and then burned. The hot gases are then sent to the gas turbine. In a closed cycle a heat exchanger is added between the turbine outlet or exhaust section and

to the inlet section of the compressor.

The purpose of this study is to conceptually integrate this hybrid power system within an existing coal gasification technology. The Kellogg Brown Root Transport Reactor was selected mainly due to the availability and location of the system which has already been visited by fellow researchers and myself. Also detailed gasifier output results have been obtained by the assistance of two of their research engineers from Southern Company. Using FORTRAN as the primary programming language and a solid oxide fuel cell program which was created by Dr. Comas Haynes[2], economic and environmental comparisons between the new integrated system and a standard pulverized coal power plant will also be made.

[2] Haynes, C., & Wepfer, W, Design for Power of a Commercial Grade Tubular Solid Oxide Fuel Cell, Energy Conversion & Management Vol. 41 1123-1139, Elsevier Science Ltd. 2000.

CHAPTER IV

SYSTEM MODELING

The investigation of the solid oxide fuel cell and gas turbine performance while at the same time allowing the KBR gasifier syngas output to "fuel" the cell will currently be performed on a modified SOFC stack program. The fuel cell program was developed by Dr. Comas Haynes[3] in FORTRAN programming language and includes the bottoming turbine cycles.

4.1 System Description

The system configuration, is displayed by figure 4.1.1, state 1F is the amount of ambient airflow required for the compressor to achieve a minimum of 2 atm of pressure before going through the intercooler. 2F is the compressed air entering in the intercooler while 3F is the air leaving at the same temperature as 1F but with the same pressure as 2F. State 4F is the air exiting the second stage compressor at a temperature less than 2F and a pressure greater than 3F, also the air is then divided into two sections. State 1 flows into the combustor chamber while the remainder flows into the recuperator. State 5F is the heated air exiting the recuperator and entering the fuel cell stack. Use of

[3] Haynes, C., & Wepfer, W, Design for Power of a Commercial Grade Tubular Solid Oxide Fuel Cell, Energy Conversion & Management Vol. 41 1123-1139, Elsevier Science Ltd. 2000.

this process stream also eliminates the need for a preburner. State 1 is the syngas fuel

flow from the Kellogg Brown and Root gasifier to the fuel cell stack. Because the gasifier operates at an average pressure of 22 atm, a series of pressure reducing valves between the gasifier and the fuel cell stack are needed to achieve a pressure of 3 atm so that the SOFC stack can operate properly. Due to recent advances in gasifier technology, we can now run the gasifier at ambient pressure, but a significant increase in cost capital will result. State 2 is the residual fuel flow from the fuel cell stack to the combustor. It was also noted that due to the large amounts of nitrogen (N_2) present, the possibility of being unable to combust the remaining fuel and power the gas turbine is in jeopardy due to the dilution of the fuel stream. State 4 is the turbine outlet exhaust which enters the recuperator and exits through the exhaust port (state 5) which must have a temperature between 20 to 40 F higher than the acid dew point of 350 F in order to prevent corrosion and sulfur condensation.

4.2 Integration of Haynes' Fuel Cell Program with Gasifier Systems

Haynes' fuel cell program was initially designed for use with methane (CH_4) Gas[4]. In order to simulate a transport reactor syn gas and integrate it with the fuel cell Program, southern company engineer Luke Rogers provided the transport reactor's actual performance outputs (table 4.2.1). Once the syn gas composition and its exiting characteristics were known, the fuel cell program was modified and results were compiled and graphed (see chapter 5 for results).

[4] Haynes, C., & Wepfer, W, Design for Power of a Commercial Grade Tubular Solid Oxide Fuel Cell, Energy Conversion & Management Vol. 41 1123-1139, Elsevier Science Ltd. 2000.

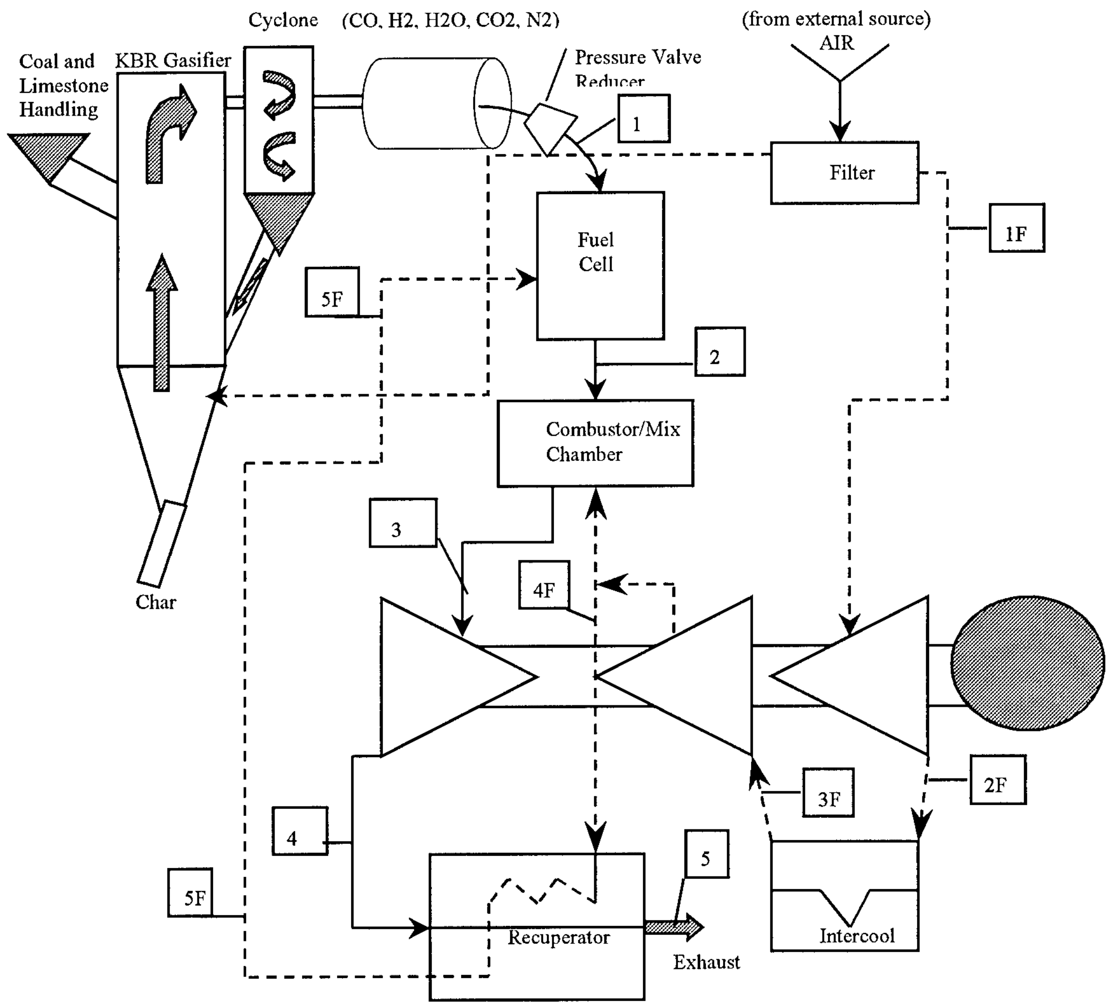

Figure 4.1.1 System Configuration

Syngas	mole %	Coal	wt%
Ar	0	Heating Value (LHV) (Btu/lb)	11497
CH4	1	C	64.39
CO	18.1	H	4.93
COS	0.011	O	10.68
CO2	8.46	N	1.21
H2	19	S	3.48
H2O	6.6	Ash	12.44
H2S	0.55	H2O	2.9
NH3	0.026		
N2	46.253		
O2	0		
Total	100		
Heating value(LHV) (BTU/SCF)	122.94		

Carbon conversion		0.9
Coal flow rate for calculations	(lb/hr)	100
Air Flow Rate	(lb-mole /100 lb coal)	8.862395579
Air Flow Rate	lb/100 lb coal	255.5914885
Air/coal ratio	(lb/lb)	2.555914885
Nitrogen flow rate	lb/100 lb coal)	30
steam flow rate	(lb/100 lb coal)	41.604945
Ash flow rate	(lb/100 lb coal)	18.879
total syngas	lbs/100 coal	408.3174335
syngas mol. wt.		23.66726
syngas heating value (LHV)	btu/lb	1865.996859
Gas temp, F		1800
Ash temp, F		1800
Steam temp, F		630
Air temp, F		600
Nitrogen temp, F		295
Coal temp, F		100
% Heat loss from gasifier to atmosphere		0.5

Table 4.2.1 KBR syngas composition and system outputs

4.3 Assumptions

The basic assumptions for design are now described. All optimal and base case fuel cell stack operating parameters were used except when a particular parameter was selected to be varied (see table 4.3.1 fuel cell stack parameters). All external sources of air are at ambient temperature and pressure. The syngas constituent, carbon sulfate was neglected, due to its negligible presence (0.011%). In the bottoming cycle it was noted, by the Southern Company engineer, that a gas expander could have been used in place of the gas turbine because the theoretical model gas turbine has the demonstrates similar characteristics as a gas expander where pressure is concerned because the pressure at state 2 is not .5 to 1 atm higher than state 4F (see figure 4.1.1). The exhaust at state 5 is at the ideal exiting temperature of 375 F, which is higher than the acid dew point.

Parameter (Units)	Value
Operating Voltage (Volts)	0.6
Pressure (Atm)	3
"Number of Stoichs"/Inverse Equiv. Ratio	3
Fuel Utilization	85
Steam-to-Fuel Ratio	3.5
Compressor Isentropic Efficiency (%)	83
Combustion/Mixing Unit Efficiency (%)	98
Turbine Isentropic Efficiency (%)	83
Cell Stack Inverter Efficiency (%)	95
Generator Efficiency (%)	98
Turbine Inlet Temperature (K)	1250

Table 4.3.1 fuel cell stack parameters

Assumptions and reasoning for proposed benefits of integration were that the KBR gasifier's raw syngas temperature is very close to the fuel cell stack's optimal fuel

receiving temperature (1800-1900 F). Also the flexibility of the gasifier sizing and modularity of SOFCs appear to facilitate matching the technologies. A SOFC/GT hybrid power system offers the most efficient and environmentally safe power module for coal gasification technology.

The parameters on table 4.3.1 were selected because of previous performance results from Haynes[3] and Bessetts[4] research and results concerning SOFCs. The operating voltage of .6 volts is the peak average at which the SOFC will achieve its highest efficiency when this parameter is varied and all others are held constant this also holds true for the stoichiometric number and pressure. Also the 3 atm is the ideal SOFC stack operating pressure recommended by Siemens Westinghouse. The compressor and turbine efficiencies were determined by the average turbine and compressor efficiencies on the market during the years 1999 to 2000, this also holds true for the combustion mixing unit and the generator efficiency.

4.4 Parameters to be Varied

The parameters listed on table 4.4.1 were chosen mainly because of their overall influence on the fuel cell stack, bottoming cycle, and or on the overall system efficiency. Also these parameters can assist in the purchasing of equipment outside the fuel cell and the gasifier. The operating voltage range of 0.5 to 0.65 will show us if the average peak

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[2] Haynes, C., & Wepfer, W, Design for Power of a Commercial Grade Tubular Solid Oxide Fuel Cell, Energy Conversion & Management Vol. 41 1123-1139, Elsevier Science Ltd. 2000.

[3]Bessette, N.F & Wepfer, W.J., A Mathematical Model of a Solid Oxide Fuel Cell, Electrochemical Society Vol. 142, No. 11, The Electrochemical Society Inc. 1995.

voltage still holds true when the fuel cell stack is integrated with the gasifier. The stoichiometric number can be easily varied and plays a major role in the combustion process. Fuel utilization is also being varied so that an optimal fuel flow from the gasifier to the fuel cell stack and be determined. Varying compressor and turbine efficiency will determine if the system will have a significant increase or decrease in power and will assist in cost projection when creating the bottoming cycle.

Varied Parameter (Units)	Range
Operating Voltage (Volts)	0.5 - 0.65
"Number of Stoichs"/Inverse Equiv. Ratio	2.5 -5.5
Fuel Utilization	0.75 - 0.9
Steam-to-Fuel Ratio	2.0 - 3.0
Compressor Isentropic Efficiency (%)	0.7 - 0.95
Turbine Isentropic Efficiency (%)	0.7 - 0.95
Turbine Inlet Temperature (K)	1250 - 1500

Table 4.4.1 varied parameters

During the early stages of experimental runs, one parameter was varied while all others remained constant. Those parameters which made noticeable impacts on the system were then varied in combination with two or more other parameters. The measured areas of the system are in the areas of optimization of system efficiency, heat exchanger effectiveness, cell power, and system power, the results of which are seen in the next chapter.

CHAPTER V

RESULTS

5.1 Parameters and Efficiency Equations

The results are presented according to the perimeters varied vs. the output results concerning cell power, system power, system efficiency, recuperator power. The program was also run for various combinations of system parameters which were able to make a small to significant impact on any one of the system output equations below. The effects these combinations had on the fuel cell stack, and the bottoming cycle assisted in the determination to discontinue or continue research in and eventual physical integration of these power systems. The cell power (equation 5.1.1) is the amount of electrical power produced per fuel cell. In order to find the total fuel cell stack power this equation must be multiplied by 2496, which is the total number of cells in a stack. The cell power uses the difference between the Nerst potential and the operating voltage of the fuel cell in order to determine the power. The Nerst potential is the largest potential electrical difference between the anode and cathode electrodes.. The system power (equation 5.1.2) is the sum of the bottoming cycle power, which is the difference between the turbine and compressor power, and the cell power. The system electrical efficiency is the ratio of the system power per cell and the syngas heating value which was produced by the transport reactor gasifier. The recuperator effectiveness is determined

by a basic heat exchange equation which finds the ratio of the difference in the heat transfer in the pre heated air and the temperature difference between the hot and cold streams (equation 5.1.4). These equations were chosen because it was determined that these efficiencies and power equations could also assist in determining the cost of bottoming cycle equipment.

Description of equations:

Cell Power: $$I_{cell} * V_{operate} = \frac{(E_{avg} - V_{operate}) * V_{operate}}{R_{effective}}$$ Equation 5.1.1

System Power: (per cell) $$P_{cell} + P_{turbine} - P_{compressor}$$ Equation 5.1.2

System Efficiency: (electrical) $$\frac{\text{System Power}}{\text{Syngas Heating Value (per cell)}}$$ Equation 5.1.3

Recuperator: Effective $$\frac{\text{Heat Transfer in air pre-heat}}{C_{min} * (T_{hot} - T_{cold})}$$ Equation 5.1.4

5.2 Data Outputs and Efficiency Comparison

The fuel cell and gas turbine cycle outputs show that the variation of some parameters create a major impact on either both systems, one system, or none of the systems. Efficiency and power generation results are designed to show the optimal combination of varied parameters and how those parameters effect each system so that many other parameter combinations could be pursued in the future.

The fuel cell stack is more efficient at a lower fuel utilization and higher fuel flow rate. If fuel utilization is increased (which also decreases fuel flow) cell power decreases and eventually the SOFC stack becomes starved for fuel. (see figure 5.2.1).

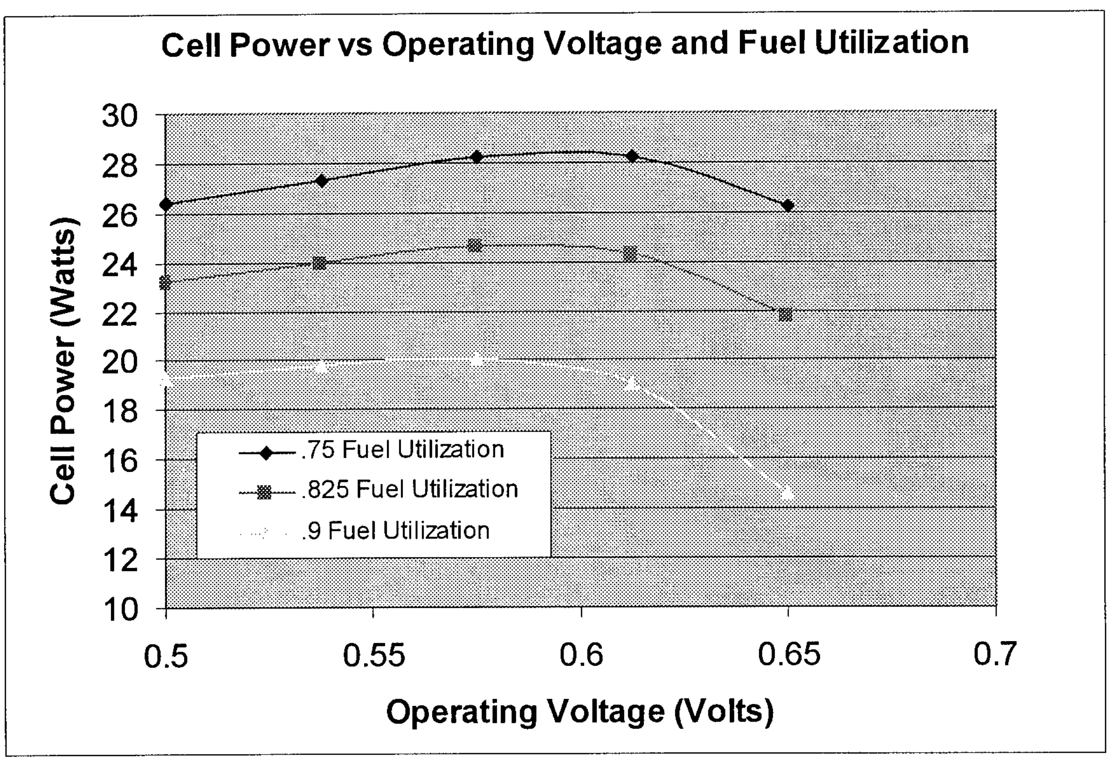


Figure 5.2.1 Cell Power vs. Operating Voltage and Fuel Utilization

Figure 5.2.1 illustrates the effects of increasing fuel utilization and operating voltage on the fuel cell stack. The higher the inert nitrogen content in the syngas to the system, the less power generated by the fuel cell. In a fuel cell using methane and oxygen the cell power would start at approximately 170 W and drop to 90 W (from Haynes report). The diluting effect of nitrogen in the syngas is also noticeable in the order of magnitude of power reduction, as depicted by the negative curve after 0.6 V. Also the maximum seen on each curve is due to the competing effects of voltage increase, because the operating voltage approaches a value which is half of the Nernst potential value.

System power (per cell), which is calculated by equation 5.1.2 combines the fuel cell power output with the bottoming cycle power, which is a slightly modified Brayton cycle.

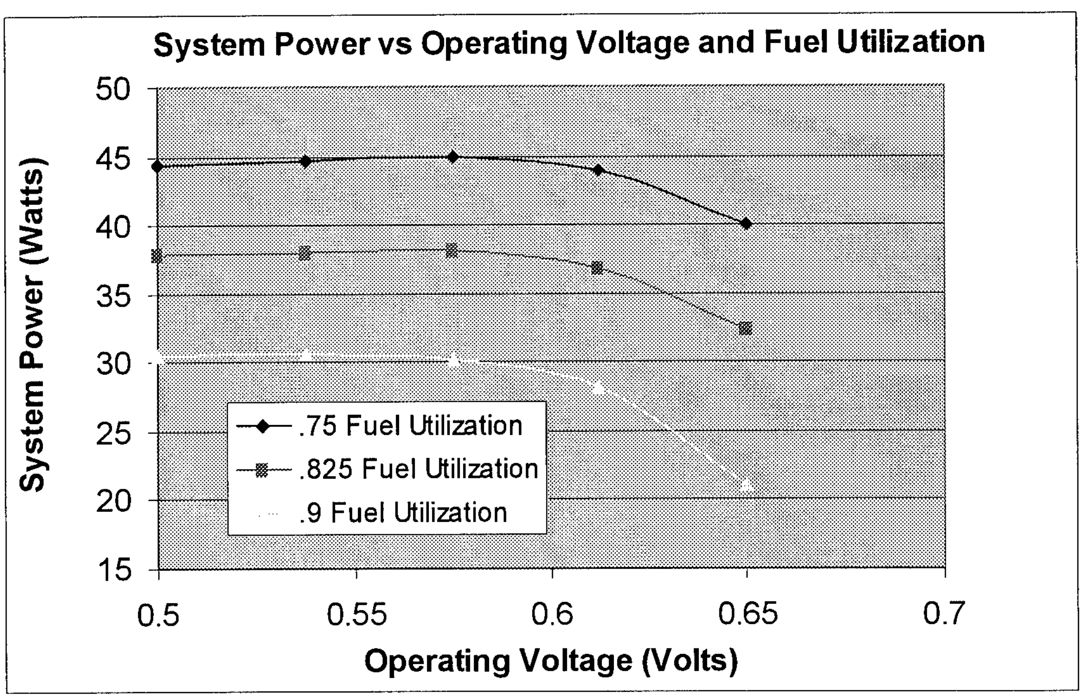


Figure 5.2.2 System Power vs. Operating Voltage and Fuel Utilization

Figure 5.2.2 illustrates the increase in power due to the inclusion of the turbo-machinery power generation. At higher operating voltages the fuel cell becomes more efficient since a greater portion of chemical energy is being converted directly to electricity. Also, not as much thermal energy is generated from the chemical energy of the fuel cell, and over all system power becomes more dependent on fuel cell power and less dependent on turbo machinery power. At 0.6 volts 63% of the system power is from the fuel cell, at 0.65 volts 65% is from the fuel cell. At lower voltages, curve is almost flat due to the increase dependence on the turbo machinery power.

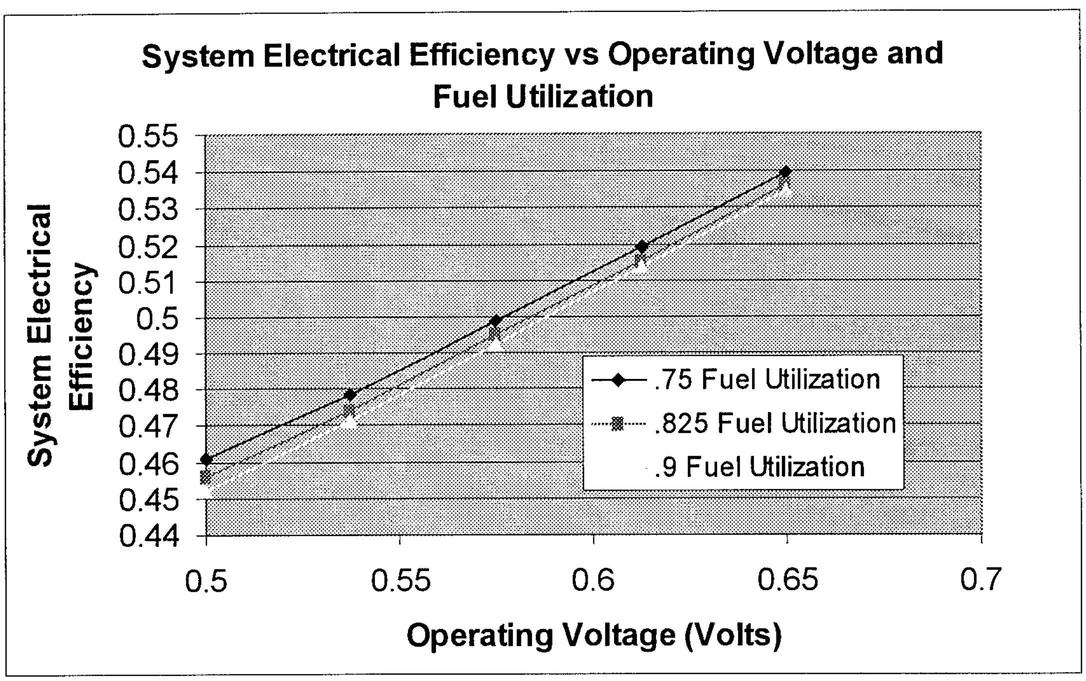
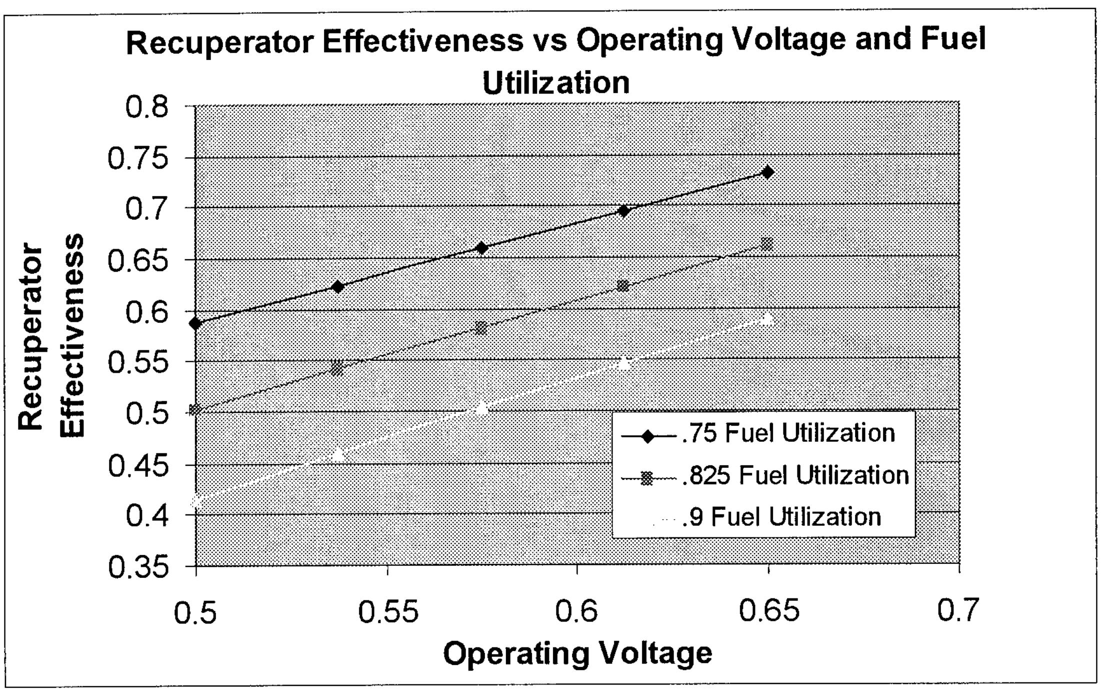


Figure 5.2.3 System Electrical Efficiency vs. Operating Voltage and Fuel Utilization

Figure 5.2.3. illustrates the linear dependence of operating voltage and electrical efficiency. This is due mainly to the operating voltage effects on system power. As the system power increases so does the electrical efficiency. Refer to equation 5.1.3, fuel utilization does not impact the linear dependence but it does effect the magnitude of the system electrical efficiency by increasing it from 0.5 – 1.0% because the unused fuel is sent to the combustion chamber where it is used to power the bottoming cycle.



Recuperator effectiveness, calculated by equation 5.1.4, is primarily dependent on the entering and exiting temperatures. Recuperator efficiency measurement is vital to monitoring total system efficiency. When the gas is exhausted from the hot side of the recuperator, it is imperative that the exiting temperature be at least 25 F greater than the acid dew point, anything less and the system will have corrosion problems. A very high exhaust temperature is also a negative because of the loss of heat energy.

Figure 5.2.4 Recuperator Effectiveness vs. Operating Voltage and Fuel Utilization

Figure 5.2.4 illustrates a linear dependence of recuperator effectiveness on operating voltage. From previous slides, an increase in operating voltage showed a decrease in cell power which means that an increase in fuel flow occurs, but less fuel is utilized in the fuel cell. The residual fuel is sent to the combustion chamber and then to the turbine, after being exhausted from the turbine the hot stream will increase in temperature and increase the heat transfer of the exchanger. This is primarly why, as mentioned in previous graphs, a decrease in fuel utilization produces an increase recuperator effectiveness.

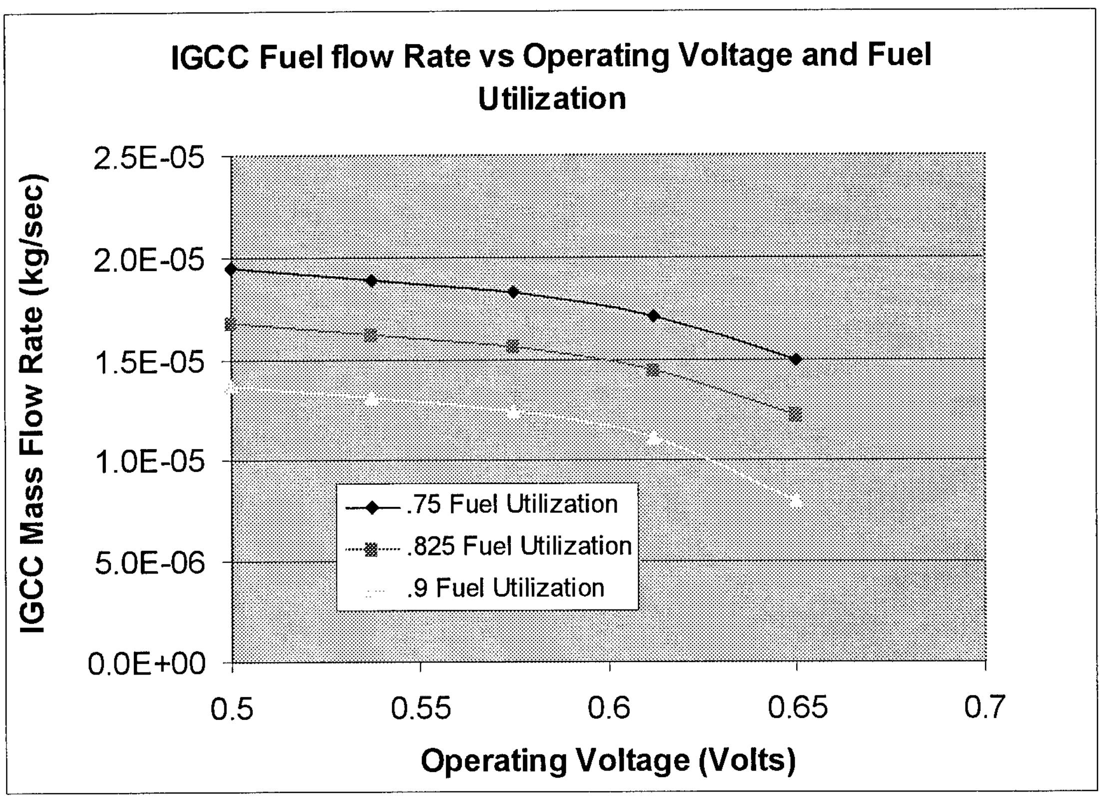


Figure 5.2.5 IGCC Syn Gas Mass Flow Rate to Fuel Cell Stack (per cell)

On a larger scale figure 5.2.5 would be a straight line. The mass flow rate of the gasifier's syngas fuel flow to the fuel cell stack is only slightly effected and is only seen when the entire fuel cell stack of 2496 fuel cells are calculated.

The steam to fuel ratio creates a diluting effect in the fuel stream, but at the same time increases heat energy. The fuel cell stack benefits more from a slightly lower temperature but heavily concentrated fuel stream then a high temperature diluted fuel stream.

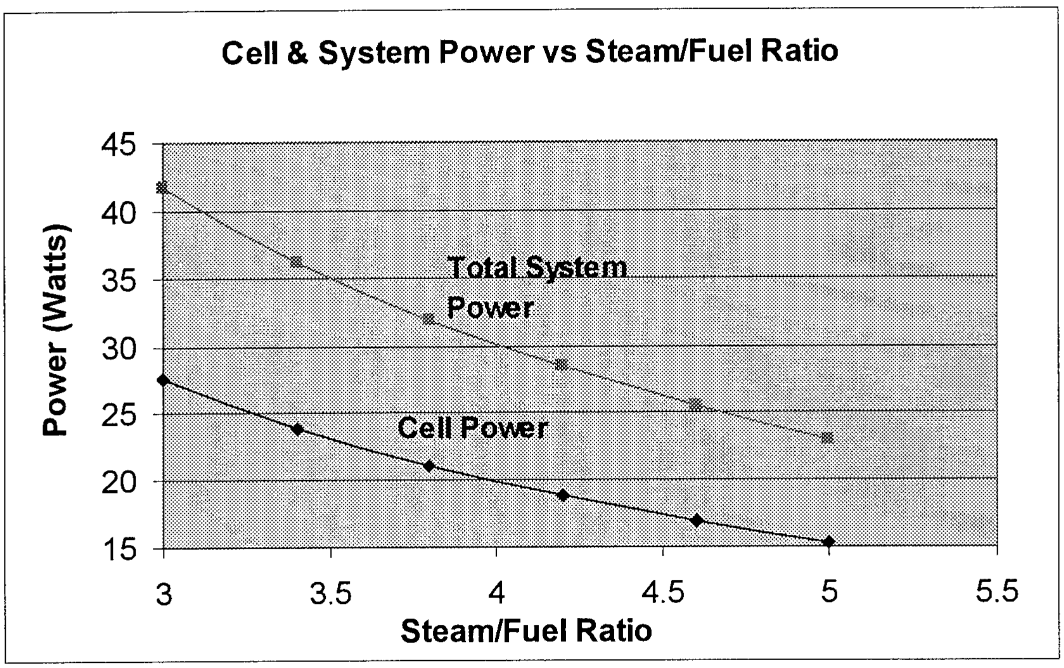


Figure 5.2.6 The effects of the Steam/Fuel Ratio on Cell and System Power

Figure 5.2.6 illustrates the diluting effect of steam which in turn causes a reduction in cell power generation. Although lower steam to fuel ratios (SFR) will increase system and cell power, carbon compound build-up, called coking, will begin to form around the fuel cell's anode and fuel processing section. System constraints prevent

a SFR less than 2.5 (and in some combinations no less than 3) to be used. The bottoming cycle is effected by the fuel cell stack by way of the anode of the fuel cell, which will yield an exhaust that is in turn combusted and powers the bottoming cycle.

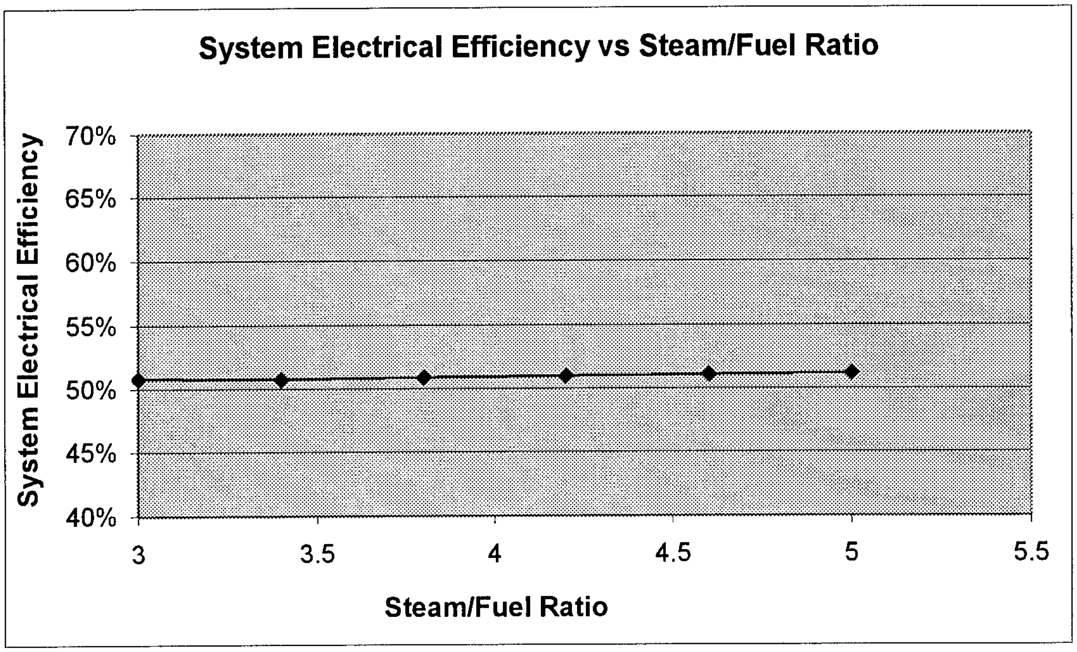


Figure 5.2.7 The Effects of the steam/fuel Ratio on System Electrical Efficiency

The steam/fuel ratio is primarily for the prevention of coking in the fuel cell stack and does not effect the bottoming cycle electrical output. From the previous slides, the fuel flow and system power are effected in a negative manner when an increase in steam is introduced, but Figure 5.2.7 illustrates that the steam/fuel ratio has a minimal impact on the system electrical efficiency due to the syngas flow rate decreasing at a constant rate with system power (see equation 5.1.3).

Figure 5.2.8, the effects of the steam/fuel ratio on the recuperator effectiveness also yields the similar results as the effects on electrical efficiency. These results are mainly due to the recuperator's location in the bottoming cycle, its primary dependence on turbine and compressor outlet temperatures, and a constant operating voltage of 0.6 V. (see voltage baseline parameter table 4.3.1)

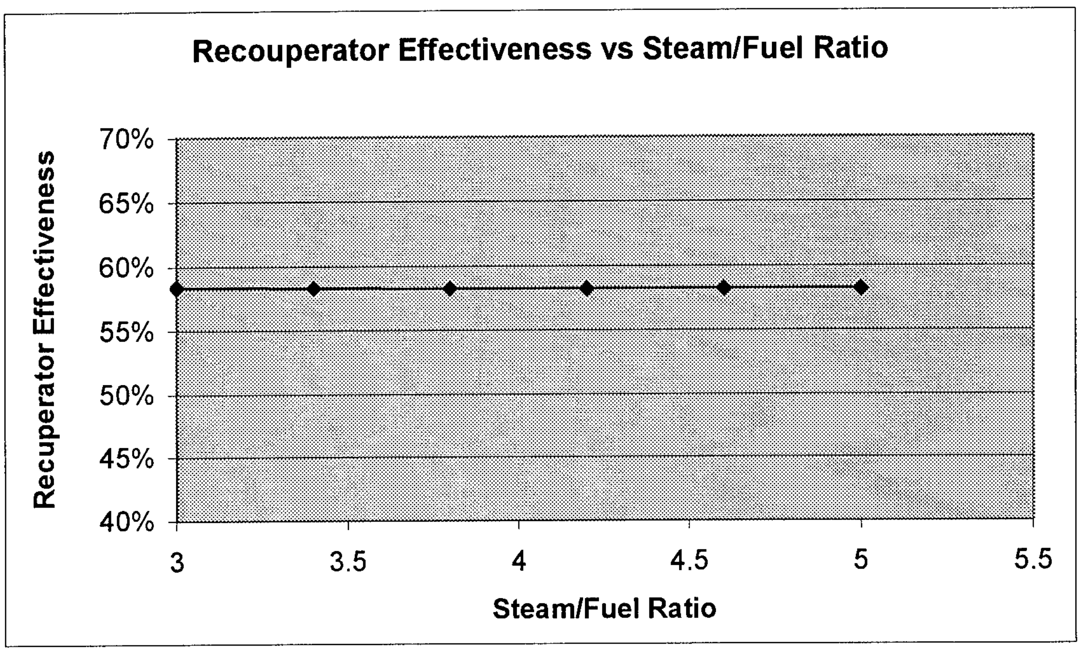


Figure 5.2.8 The Effects of the Steam/Fuel Ratio on the Recuperator Effectiveness

The stoichiometric number, which is the ratio of actual air and theoretical air, increases the system's potential to combust fuel. Oxygen is a major part of combustion and can also assist in decreasing the exhaust temperature exiting the recuperator. The impact of increasing the mass flow of air into the fuel cell stack and throughout the

system will yield positive results. (figure 5.2.9). The turbo-machinery benefits greatly by increased airflow, thus the system power yields a nearly linear dependence on the stoichiometric number in the positive direction.

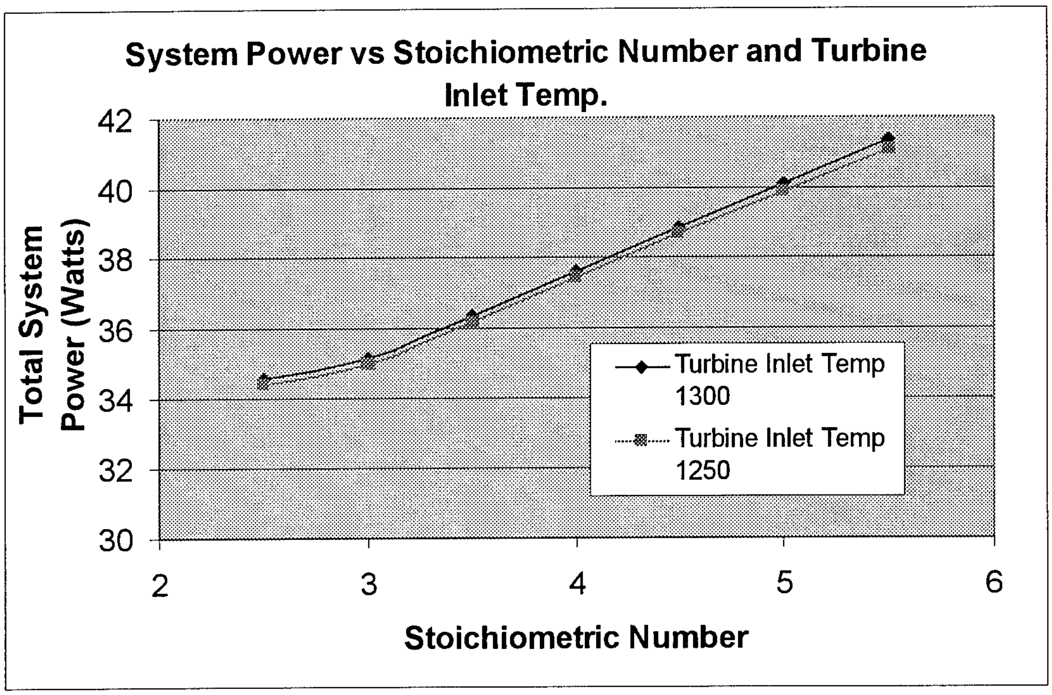


Figure 5.2.9 System Power vs. Stoichiometric Number and Turbine Inlet Temperature

Figure 5.2.9 illustrates the effects of the stoichiometric number on fuel flow. When the stoichiometric number increases then we also see an increase in the fuel cell stack inlet air temperatures which in turn allows for more power generation. This is due primarly to the fact that air greatly assists in the combustion process. The variation of the turbine inlet temperature from 1250 to 1300 F (1300F is a maximum system constraint) presents a minimal increase in power. Attempts were made to increase the turbine inlet temp. to ranges of 1800 F, but the adiabatic flame temperature cannot be less than the

turbine inlet temperature. The stoichiometric number of 2.5 and the turbine inlet temperature of 1350 was the minimum/maximum combination which the system was able to achieve without system manipulation.

Increasing the turbine inlet temperature will also assist in increasing the system electrical efficiency (figure 5.2.10). The stoichiometric number also has a major effect on system electrical efficiency.

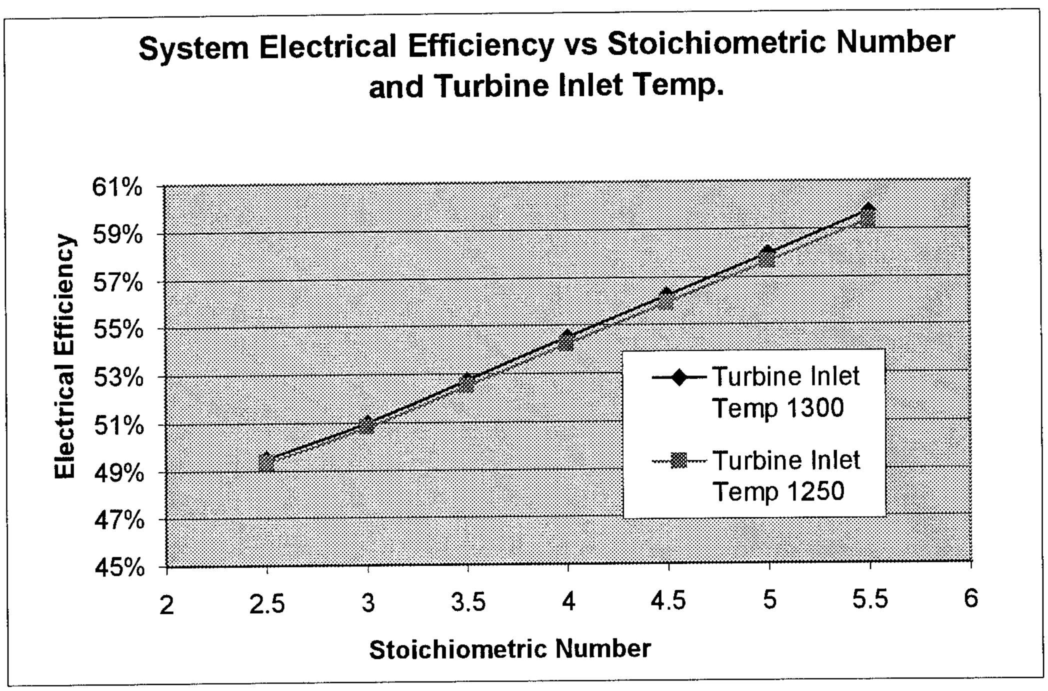


Figure 5.2.10 System Electrical Efficiency vs. Stoichometric Number and Turbine Inlet Temperature.

Figure 5.2.10 illustrates the linear dependence of the system's electrical efficiency and stoichiometric number. Also the electrical efficiency (equation 5.1.3) which is based on the system power divided by the syngas heating value (per cell), has an increase in both system power and heating value, but the system power has a much greater increase. One other interesting observation was the increase in syngas caused more nitrogen to be heated and circulated through the system. Also, since the stoichiometric number had a minimal impact on fuel cell efficiency the oxygen air stream also made a minimal contribution to the Nernst potential. So the reason for the major increase in electrical efficiency was mainly due to the bottoming cycle electrical power output.

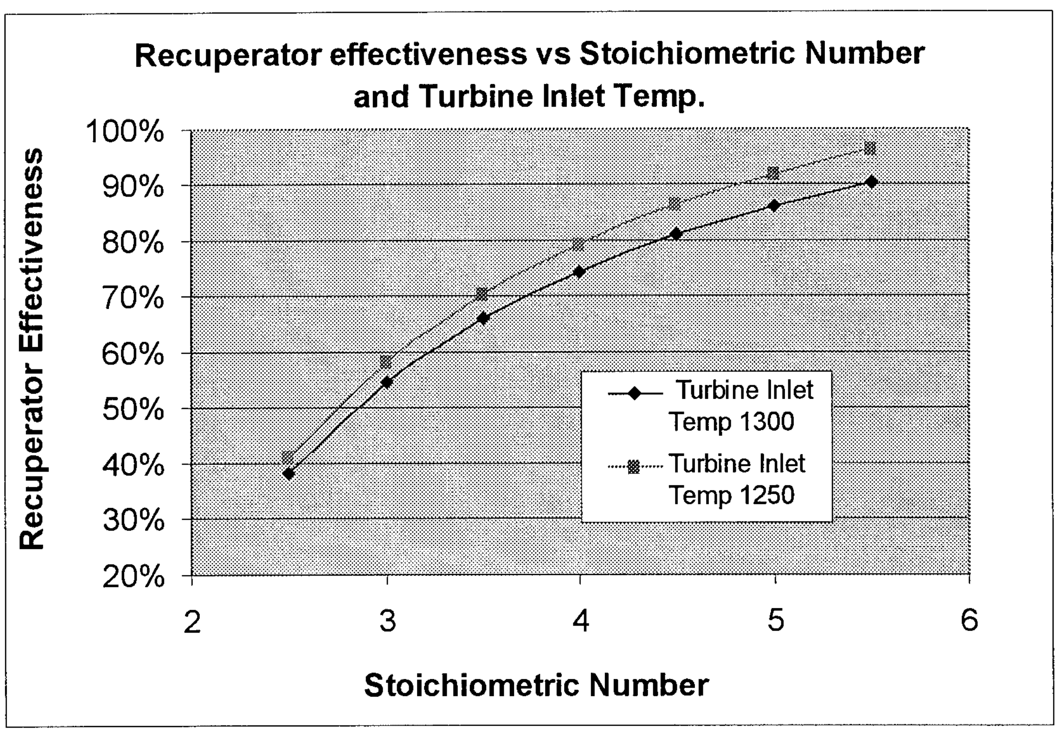


Figure 5.2.11 Recuperator Effectiveness vs. Stoichiometric Number and Turbine Inlet Temperature.

Figure 5.2.11 illustrates the change in recuperator effectiveness when the stoichiometric number increases. When the stoichiometric number is increased the fuel cell stack temperature increases as well. The recuperator will also have to increase in effectiveness because of the increase in heat exchanged from the turbine outlet temperature and the compressor outlet temperature. Although the increase in recuperator effectiveness is not linear the entire heat exchanger system must increase in size so that the increase in airflow can be accommodated.

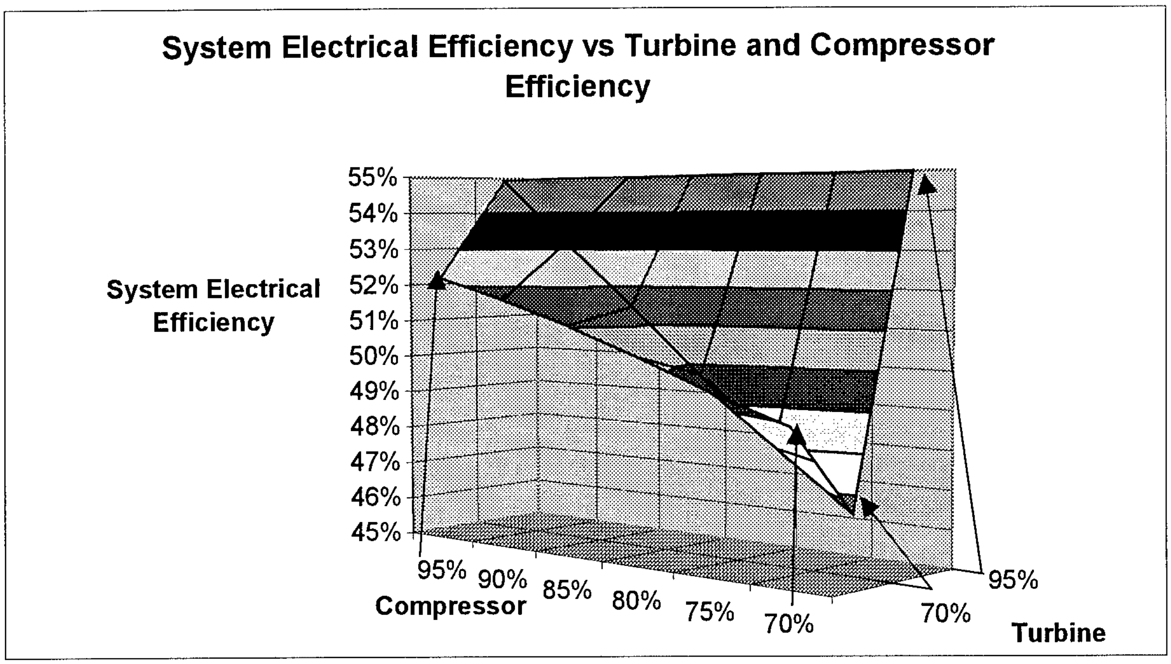


Figure 5.2.12 System electrical efficiency vs. Turbine and Compressor Efficiency

Figure 5.2.12 illustrates the linear dependency of the turbine and compressor efficiency on the system electrical efficiency. The standard parameter values previously mentioned in chapter 4 are still held constant for this graph and the next. When the

compressor efficiency was varied the turbine efficiency remained constant at 83%. When the turbine efficiency was varied the compressor efficiency remained constant at 83%. The electrical efficiency for the varying turbine efficiency did not pass the electrical efficiency which was related with the increase in compressor efficiency until the 83% mark. As the efficiency for the compressor and turbine increased, the electrical efficiency benefited more from higher turbine efficiencies because the turbine over all has a greater impact due to the fact that it also powers the compressor and generator. When the compressor and turbine efficiencies are varied simultaneously (figure 5.2.13). a mean value linear increase.

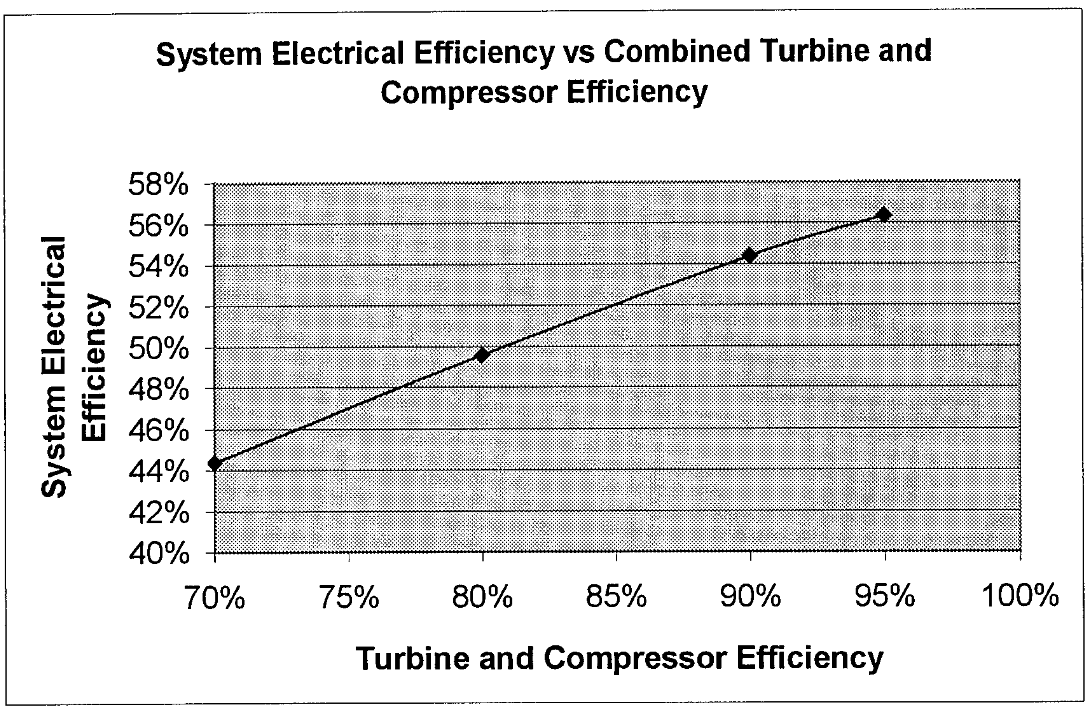


Figure 5.2.13 The Effects of a Simultaneous increase in Turbine and Compressor Efficiency on System Electrical efficiency.

Figure 5.2.13 illustrates how the simultaneous increase in turbine and compressor efficiency is not always beneficial, in that a highly efficient turbine and compressor (95%) versus one high efficient turbine (95%) and a medium high efficient compressor (83%) can still produce the similar electrical efficiencies, 56.2% and 55.5% respectively, and at a lower cost.

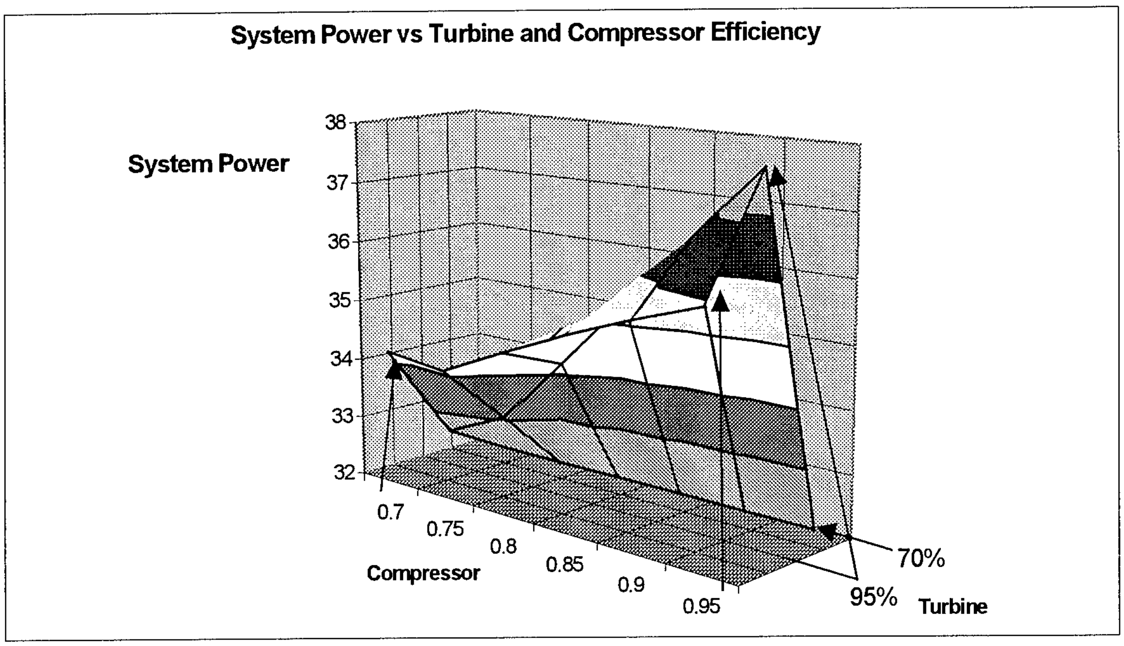


Figure 5.2.14 System Power vs. Turbine and Compressor Efficiency

Figure 5.2.14 illustrates the gradual increase in power generation resulting from the increase in turbine and compressor efficiency. The standard parameter values previously mentioned in Chapter 4 are still held constant for this graph and the next. When the compressor efficiency was varied the turbine efficiency remained constant at 83%. When the turbine efficiency was varied the compressor efficiency remained constant at 83%. The compressor efficiency from 70-75% did not begin to effect the

system power until after 76%, after which the increase became linear. The turbo-machinery made the greatest impact in power generation after the 83% benchmark.

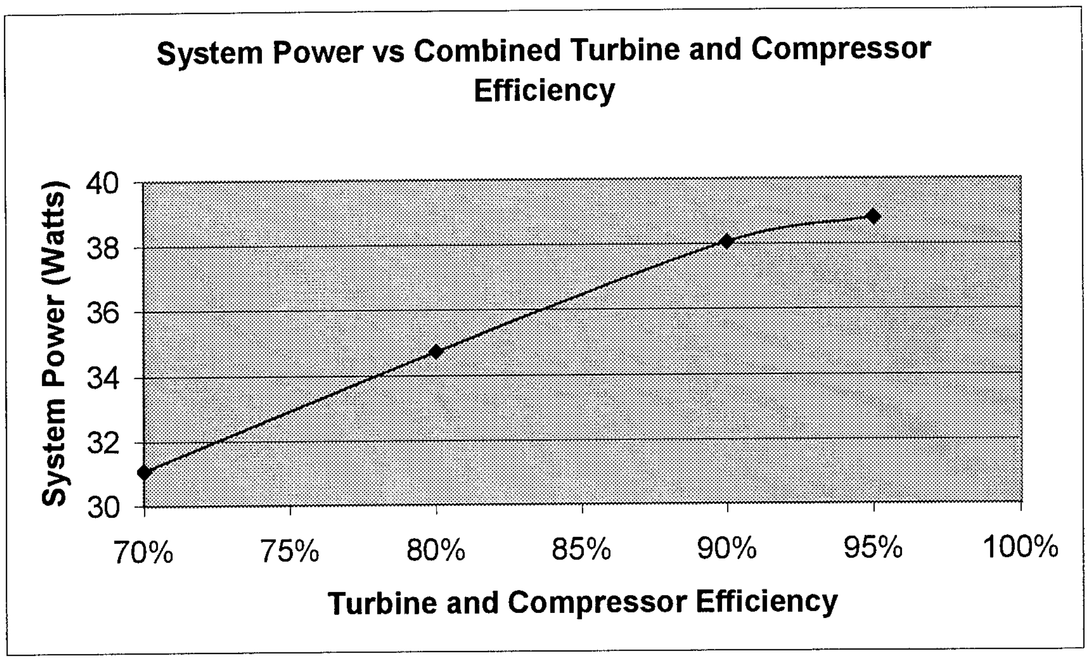


Figure 5.2.15 The Effects of a Simultaneous increase in Turbine and Compressor Efficiency on System Power.

Figure 5.2.15 illustrates how the simultaneous increase in turbine and compressor efficiency is beneficial, in that a highly efficient turbine and compressor (95%) versus one high efficient turbine (95%) and a medium high efficient compressor (83%), yields a much higher system power output, 39 W and 37.5 W. This graph also shows that it is more beneficial to purchase a higher efficiency turbine than a higher efficiency compressor; however, product cost versus an increase in power by 1.5 W (per cell) is magnified when the calculation of total stack power is performed (total stack power =2496 *power per cell).

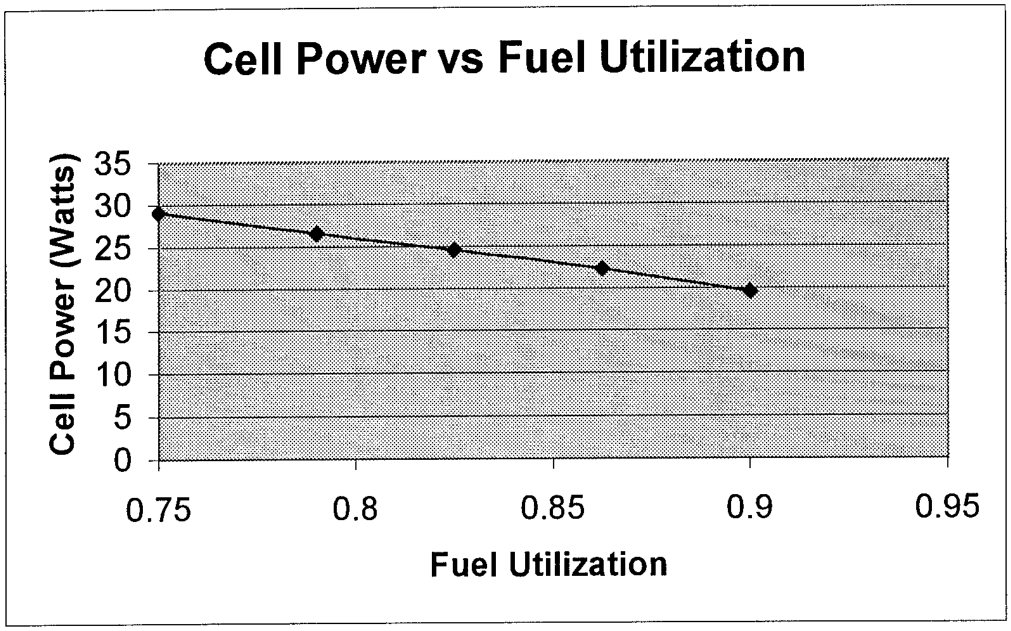


Figure 5.2.16 Cell Power vs. Fuel Utilization

Fuel utilization continues to create a negative effect on the system as whole. The increasing percentage of nitrogen is believed to be the major cause of the degradation of the fuel stream.

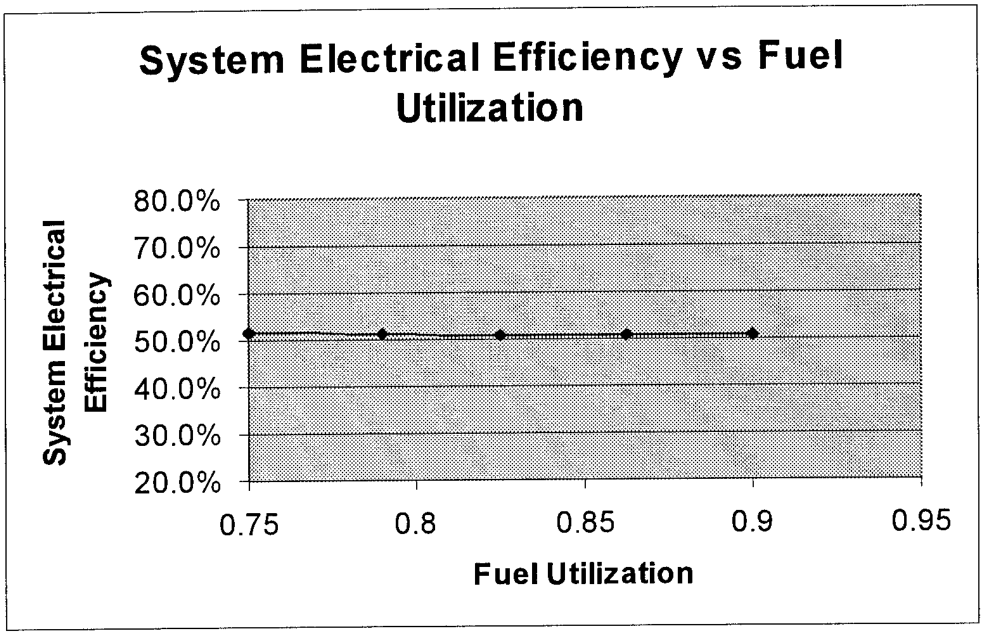


Figure 5.2.17 The effects of Fuel Utilization on System Efficiency

From figures 5.2.17, fuel utilization's impact on system efficiency is fairly stable due to enhanced re-circulation, but a corresponding decrease in stack inlet air temperature exists; hence, a decrease in recuperator effectiveness.

This chapter has described how the variations in several key parameters effects system performance. In the next chapter (conclusions/recommendations), the importance of these competing variations will be discussed.

CHAPTER VI

CONCLUSIONS / RECOMMENDATIONS AND PROPOSED FUTURE CYCLE INTEGRATIONS

Initial expectations concerning the integration of the SOFC and the KBR reactor gasifier did not support our assumption that this integration should continue to be researched for this particular application. The results showed a significant decrease (an order of magnitude) in all measured outputs when comparing the air blown gasifier syn gas with a pure methane gas entering into the fuel cell stack. The diluting presence of a large percentage of nitrogen (46%) had a negative effect on the fuel stream when it reacted within the fuel cell stack. Also the small traces of sulfur aided in the degradation of the fuel stream. Although expectations were that there would be a decrease, it was not expected to be at the magnitude previously mentioned.

Due to the recent advancements in technology, the construction of oxygen blown gasifiers are now at a level where they are projected to be relatively close to price of air blown gasifiers. The oxygen blown gasifier design filters out the nitrogen which yields a syngas that could be suitable for fuel cell stack consumption. Also the design of the bottoming cycle would call for the removal of the intercooler because it is no longer a commonly used item in power generation. The combustor-mixing chamber would also

be removed, due to the fact that today's gas turbine has a combustor built into it and has even higher efficiencies then what was previously known. The gasifiers are able to operate at output pressures of 3 atm or less, but the cost capital would be increased due to larger size hardware. A proposed recommended model for future study (figure 6.1.1) shows the changes previously mentioned. The actual parameters and necessities for an oxygen blown gasifier to be integrated with a SOFC stack are currently unknown. Theoretical projections, which were mainly based on clear patterns and proven chemical reactions, show that if the presence of nitrogen was removed from the syn gas then the output would be similar to that of an oxygen blown gasifier. With the nitrogen being removed from the syn gas, the cell and system power outputs would increase by almost a factor of 6 when compared to the results previously discussed in chapter 5. The system electrical efficiency levels would also increase by 8.5%. The cost of integration is currently unknown; however, new Department of Energy reports have stated that the price of construction and operation of an oxygen blown gasifier may soon decrease and would be comparable to the existing air blown gasifiers. It is the conclusion of this investigator that the pursuit to integrate a fuel cell stack with a gasifier should continue in the direction of oxygen blown transport reactors.

As a first order conclusion, it is helpful to contrast the current state of fuel cell coal gasification technology with state-of-the-art combustion turbine technology.

Current combustion-turbine systems used by utilities for power generation can be purchased for $240/kW and have efficiencies on the order of 35%, those systems with steam Rankine bottoming cycles, (steam produced from exhaust, called a combined

cycle), can be purchased for \$562/kW with an on the order of 52% efficiency. The current price of natural gas ranges from \$0.4660 to \$0.7290 per therm. (\$4.66 to \$7.30 per mmBtu) for the State of Georgia. Also \$0.3779 per therm. (\$3.80 per mmBtu) is the current national average from the Wall Street Journal. These systems are the current gold standard of power generation.

For the theoretical SOFC stack and KBR gasifier combination, each system can be purchased for \$1305/kW and \$1000/kW respectively, and have a combined efficiency on the order of 51% (at optimal recommended parameters, see table 4.3.1). The current price of coal ranges from \$0.04 to \$0.12 per lb.

The proposed theoretical SOFC stack and oxygen gasifier combination, each system can be purchased for \$1305/kW and \$1600/kW respectively, and have a combined estimated efficiency on the order of 58% to 62% (at optimal recommended parameters, see table 4.3.1). The current price of coal ranges from \$0.04 to \$0.12 per lb.

In order for these theoretical systems to begin to become competitive with current combustion turbine power plants, the cost of capital must decrease for oxygen gasifier technology, and the price for a solid oxide fuel cell stack must also decrease. Also a complete study of cost estimates for physical integration between these two systems must be researched.

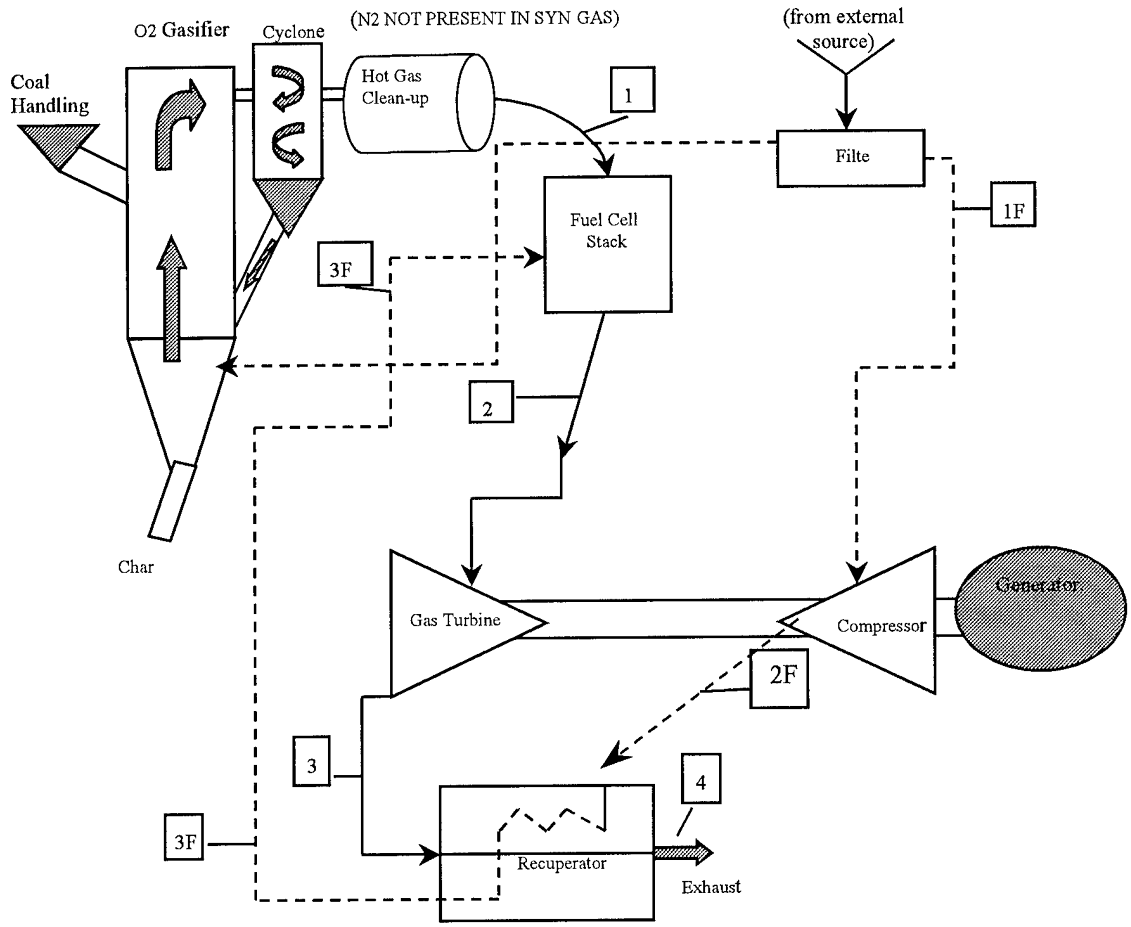


Figure 6.1.1 Recommended future integrated model

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